

Final Report on NAG5-11124: Determining the importance of energy transfer between magnetospheric regions via MHD waves using constellations of spacecraft
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This grant was focused on research in two specific areas: (1) development of new techniques and software for assimilation, analysis and visualization of data from multiple satellites making in-situ measurements; and (2) determination of the role of MHD waves in energy transport during storms and substorms. Results were obtained in both areas and presented at national meetings and in publications. The talks and papers that were supported in part or fully by this grant are listed in the References section below.

The research on new techniques and software resulted in software for 3d visualization of data from a cluster of satellites. An example of 2d snapshots in time from the 3d visualization program is shown below. The blue and green planes represent a discontinuity (orientation and velocity of the normal determined from the spacecraft potential measurement on the Cluster quartet, using the semblance methodology developed in the first year of this grant). The snapshots show the discontinuity (in this case, a bow shock crossing) propagating past the satellites. The color of the satellites represents the size of the spacecraft potential. Many additional diagnostic plots can be included, such as the magnetic field vector. Several sample movies are available at our website. The .mov files are compressed Quicktime movies. The .wrl is a VRML file which be manipulated within the browser. The viewer may need to get a plug-in to view and manipulate the VRML file. The descriptions of the movies, etc. are as follows:

orbit.mov -

Three orbits worth of data for the Cluster spacecraft.

The first half of the movie shows the orbits from a side view ($\sim +Y$ gse). The blue ball is the earth, the sun is to the left. The red lines are the traces of the Cluster center of mass for the three orbits. One can see the precession in GSE coordinates due to the earth's movement around the sun. The spacecraft are not individually visible on this scale, so are represented by a greyish sphere. Near the end of the first half, and also at the very beginning for perspective of where the sun is, a green shell appear which is a model magnetopause. The shell is uniform, the coloring differences are due to 3d perspective only.

The second half of the movie is the same 3 orbits, now riding along with the spacecraft. The 4 SC are individually represented by small spheres. One can observe the different orientations (tetrahedra, string of pearls, etc) throughout the orbits. Near the beginning, once in the solar wind, the model magnetopause is turned on again, but from the perspective of riding along, it doesn't add much, so it's just turned on that once. Although diving back into the magnetosphere is depicted for that first orbit. Going into the 2nd orbit, the SC colors are changed to indicate the SC Potential. For most of the time far away from the earth, this doesn't change very much, although it changes quite a bit near the earth. Shortly after turning on the SC coloring, the Magnetic field (minus a model in the magnetosphere) measured at each SC are shown as colored vectors.

scraj.mov -

Cluster crossing a boundary.

This is a close up of cluster crossing a boundary. This is a very short amount of time, about 1 second total, with a stationary camera. It mainly demonstrates various ways to view the data. The representations are similar to the 2nd half of orbit.mov. The color of the SC this time represent to density, devived from the SC potential, the vectors are again the magnetic field. The coloring of the magnetic field vectors are just a time index, starting at red at the begining, running through the rainbow to purple at the end.

The same data is run through 4 times to show various ways to look at the data.

- 1 - Showing the data moment by monent, like a movie.
- 2 - Same as 1, but trailing dots with the color of the density for previous times.
- 3 - Same as 2, but with the trailing path being continuous spheres.
- 4 - Same as 3, but trailing the vectors as well as the spheres.

After that, the final result is manipulated in 3d, as an example of perspective.

cluster.wrl -

This is basically the final data representation in scraj.mov. The user can manipulate this representation in 3d himself.



In the area of new analysis techniques, we focused on the use of the very robust semblance method. The initial use was for determining the orientation and velocity of boundaries in space, utilizing a variety of parameters including density and magnetic field. This technique has been utilized in many Cluster studies by the Space Physics group. Using the semblance method developed for finding the time delays between

arrivals of events at various satellites, we examined the question of determining the direction of the arrival of the events, without assuming any type of model for the events. The resulting algorithm, applicable to any number of satellites greater than or equal to four, was programmed in IDL, and has been tested utilizing data from Cluster in order to determine wave propagation and modes.

The 3d visualization methodology was presented at the AGU, both in scientific sessions and in one of the booths. Results obtained using the semblance techniques have also been discussed in many talks and in several recent papers.

Scientific results on the Poynting flux associated with Alfvén waves during magnetotail reconnection events and during storms and substorms have been presented. Several studies on propagation of disturbances excited by pressure pulses in the solar wind have also been reported. Several undergraduate students have performed research on these topics, including an REU student, Chelsea Tiffany, who studied excitation of dayside aurora by CME-associated compressions. A graduate student, John Dombeck, has also worked on Poynting flux during storms utilizing data at different altitudes. In addition, this grant supported the work of one postdoc, K.-H. Kim.

Talks on the work supported by this grant have been presented at numerous meetings, including the International Conference on Substorms 6 (March, 2002), the Cluster SWT (Sept. 2002), the Fall 2002 AGU, and the Princeton Workshop on Electromagnetic Waves in Reconnecting Current Sheets (February, 2003). One talk will be given at the Cluster Tail Workshop in Graz and two talks will be given at the upcoming EGS/AGU meeting. Papers have been published on a number of studies of waves in the magnetotail and the front-side magnetosphere. In addition, there are several manuscripts in preparation.

TALKS:

Cluster Observations In the Magnetotail During Sudden and Quasi-periodic Changes In the Solar Wind Dynamic Pressure, Kim, K, Cattell, C, Lee, D, Andre, M, Lucek, E and Balogh, A, EOS. Trans. AGU, 83(47), Fall Meeting Suppl., Abstract SM72A-0603, 2002.

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Observations by the Polar and Cluster Spacecraft of the Structure and Dynamics of Strong Poynting Flux in the Plasma Sheet During Periods of Strong Magnetic Activity Wygant, J R, et al., EOS. Trans. AGU, 83(47), Fall Meeting Suppl., 2002.

The Role of Waves in Magnetotail Dynamics, Cattell, C., International Conference on Substorms 6, Seattle, WA, March, 2002

Observations of the Polar and Cluster Spacecraft of the Structure and Dynamics of Strong Poynting Flux in the Plasma Sheet During Periods of Strong Magnetic Activity Wygant, J R. et al., *Eos Trans. AGU*, 83(47), Fall Meet. Suppl., 2002.

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Papers Published:

The Role of Waves in Magnetotail Dynamics, C. Cattell, J. Dombeck, J. Wygant, F. S. Mozer, and M. André, Proc. ICS6, R. Winglee, ed., UW, pg. 443, 2002.

Evidence for component merging near the subsolar magnetopause: Geotail observations Kim, K.-H.; Lin, N.; Cattell, C. A.; Song, Y.; Lee, D.-H., *Geophys. Res. Lett.*, 29, 6, pg. 41 to 43, 2002.

Magnetospheric responses to sudden and quasiperiodic solar wind variations, Kim, K.-H.; Cattell, C. A.; Lee, D.-H.; Takahashi, K.; Yumoto, K.; Shiokawa, K.; Mozer, F. S.; Andre, M., *J. Geophys. Res.*, 107, A11, SMP 36-1 to SMP 36-12, doi:10.1029/2002JA009342, 2002.

Enhanced magnetospheric/boundary layer plasma flows observed during transient magnetopause crossings, Kim, K.-H., N. Lin, C. A. Cattell, D. H. Lee, S. Kokubun, T. Mukai, K. Tsuruda, in Earth's low-latitude boundary layer, Geophysical Monograph vol 133, edited by P.T. Newell and T. Onsager, pp. 83-91, 2003.

'Multiple magnetopause crossings observed by the four Cluster spacecraft: A case study,' K.-H. Kim, C. A. Cattell, M. Andre, and A. Balogh, submitted to *J. Geophys. Res.*, 2003.

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Papers submitted or in progress:

(1) Enhanced tail electric field triggered by solar wind pressure impulse, Kim, K.-H., C. A. Cattell, D.-H. Lee, A. Balogh, M. Andre, Y. Khotyaintsev, S. B. Mende, and E. Lee, submitted to *Geophysical Research Letters*, 2004

(2) A method to determine the group velocity of a surface wave using the wave normal information from its phase fronts, Wygant, J., Kamp, W., manuscript in preparation, 2003.

(3) J. Wygant et al. , Cluster observations of an intense normal component of the electric field in the ion decoupling region at a thin reconnecting current sheet in the tail and its relation to non-adiabatic shock-like acceleration of ion beams, submitted to *Journal of Geophysical Research*, 2004,.